Grid-Connection Control and Simulation of PMSG Wind Power System Based on Three-Level NPC Converter

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Abstract

The technology of the high-voltage and high-power three-level converters are applied to the system of direct-drive wind power, and the converter structure is the dual three-level with back-to-back structure. The generation-side converter guarantees the point tracking of the maximum power and the smooth operating of the generator through the double-loop control scheme of the maximum ratio of torque to current. The grid-side converter adopts the vector control of grid voltage orientation, realizing the decoupling control of the active and reactive power. Meanwhile, the constant DC power can be ensured and the working state of the converter can be maintained in a unity power factor state. The simulation results show that the use of the dual three-level converter not only realizes the dynamic control of the system but also ensures the high quality of the electricity delivered to the grid.

Keywords

Wind Power Generation;Direct-Driven Permanent Magnet Synchronous Generator; Three-Level Converter; Double-Loop Control

Introduction

Wind is one of the most abundant renewable sources of energy in nature. Wind energy can be harnessed by a wind energy conversion system (WECS) composed of a wind turbine, an electric generator, a power electronic converter and the corresponding control system. Based on the types of components used, different WECS structures can be realized to convert the wind energy at varying wind speeds to electric power at the grid frequency. The most advanced generator type is perhaps the permanent-magnet synchronous generator (PMSG). This machine offers, compared at the same power level and machine size, the best efficiency among all types of machines with high robustness and easy maintenance due to slip-ring-less and exciter-less features. The inherent benefit of permanent magnet which supplies rotor flux in synchronous machines without excitation loss supports the wind power generation development. This thus results in the increasing use of PMSG[1]. With nominal power of wind turbines has been continually growing, Direct-drive wind turbines needs higher power converters to transform variable voltage amplitude and variable frequency power to constant voltage amplitude and constant frequency power. However, The existing switch device capacity value can't satisfy the demand of large power converter. So studing high power converter topology of direct drive wind power system and its control strategy has important theoretical and engineering value[2,3].

In order to meet the demand of wind power for high voltage, high power and high quality converter, multilevel converters, especially three-level converters, are good alternative to the conventional converters in systems. Multilevel converters permit us to increase the output-voltage magnitude, reducing the output voltage and current harmonic content, make output waveform closer to the sine wave the switching frequency, and the voltage supported by each power

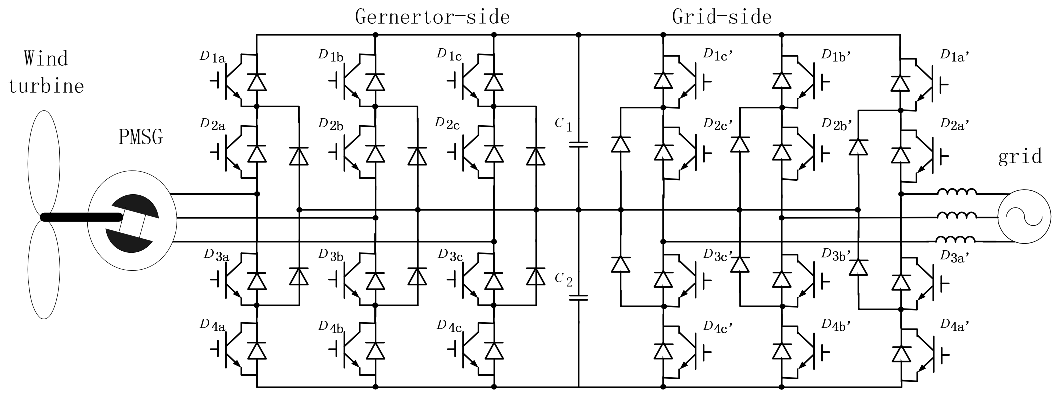


FIG.1 THE TYPOLOGY OF THE BACK-TO-BACK, THE DOUBLE THREE-LEVEL AND THE NPC CONVERTER

semiconductor[4]. A multilevel converter enables the ac voltage to be increased without an output transformer. In addition, the cancellation of low frequency harmonics from the ac voltages at the different levels means that the size of the ac inductance can be reduced, a consequent decrement of the expenses of the overall system. The presented advantages of multilevel converters make it interesting to use these kinds of power topologies as an alternative to conventional two-level converters in many renewable energy applications and industry. Multilevel converters control output frequency and voltage including the phase angle providing a fast response and autonomouscontrol. This paper adopts double three level back-to-back converter structure, that is to say, generator side and grid side converter adopt Neutral-point-clamped (NPC) three level topology. The maximum power tracking and generator stable operation can be realized by using the space voltage vector pulse width modulation and combining with double closed loop control[5]. In this system, the design of a complete analytical model of the converters is very useful to easily develop a control strategy corresponding to a specific application of the multilevel converter. The simulation results verify the correctness of theoretical algorithm and control strategy.

Model of Direct Drive Wind Power

Direct-drive wind power system ,due to the motor rotor connect with impeller directly, remove gear box which fault rate is very high, has the advantage of low noise, small volume and high stability, it will have great development space in the future.

Wind Power System Comparison

Figure 1 is the Double Three-level NPC Converter diagram. Wind turbine and permanent magnet synchronous generator are connected directly, electrical energy of generator stator passes through the full-scale converter fed into the grid.

Model of Wind Turbine

The principle of wind turbine is that wind power is converted into mechanical energy and conveyed out by wind wheel. According to the principle of aerodynamics, the wind machine output power meet [6]:

$$P_m = \frac{1}{2} S\rho V_w^3 C_p(\theta, \lambda) \tag{1}$$

$$\lambda = \omega_w R / V_w \tag{2}$$

Where S is blade swept area, ρ is air density, V_W is wind speed, θ is blade pitch angle, λ is tip speed ratio, ω_w is wind wheel speed, R is wind machine rotor radius, C_P is Power coefficient relate to θ and λ.

Due to wind machine caught power from the wind meet:

$$P = T_w \omega_w \tag{3}$$

So the wind machine output torque can be expressed as:

$$T_w = \frac{1}{2} \rho \pi R^3 V_w^2 C_p(\theta, \lambda) / \lambda \tag{4}$$

The equation of motion for the wind turbine is:

$$\frac{d\omega_r}{dt} = (T_\varepsilon - T_w - B_m \omega_r) / J_{\varepsilon q} \tag{5}$$

Where ω_r is rotor speed. T_e is electromagnetic torque. B_m is equivalent moment of inertia. J_{eq} is

rotational viscous coefficient.

Model of Generator

PMSG voltage and flux linkage and torque and the motion equation is as follows in dq0 coordinate.

$$\begin{cases} U_{sd} = -R_s i_{sd} + \omega_r L_q i_{sq} - L_d \dfrac{di_{sd}}{dt} \\ U_{sq} = -R_s i_{sq} - \omega_r L_d i_{sd} - L_q \dfrac{di_{sq}}{dt} + \omega_r \psi_f \end{cases} \quad (6)$$

$$\begin{cases} \psi_{sd} = L_d i_{sd} + \psi_f \\ \psi_{sq} = L_q i_{sq} \end{cases} \quad (7)$$

$$T_e = \frac{3}{2} N_p i_{sq} \left[(L_q - L_d) i_{sd} + \psi_f \right] \quad (8)$$

$$T_m - T_e = \frac{J}{N_p} * \frac{d\omega_r}{dt} \quad (9)$$

Where U_{sd} and U_{sq} is stator d and q-axis voltage. R_s is stator resistance. L_d and L_q is genertor d and q-axis inductance. T_m is mechanical torque. J is moment of inertia. N_P is the number of pole-pairs.

Control Strategy of System

Control Strategy of Generator-Side Converter

The control objectives of generator-side converter is guaranting the point tracking of the maximum power and the smooth operating of the generator[8,9].We use maximum ratio of torque to current control strategy to accomplish this goal. The relationship between electromagnetic torque T_{en}, i_{dn} and i_{qn} is as follows[7].

$$\begin{cases} T_{en} = \sqrt{-i_{dn}(1 - i_{dn})^3} \\ i_{qn} = \dfrac{1}{2}\sqrt{(1 - 2i_{dn})^2 - 1} \\ i_{dn} = \dfrac{1}{4}(1 - \sqrt{1 + 8i_{sn}^2}) \end{cases} \quad (10)$$

The simulation using convex stage generator parameters, $L_q > L_d$ .When PMSG using the maximum ratio of torque to current control trategy, $i_d < 0$,in other words, the essence of this control scheme is to use direct axis current demagnetization effect. So we can control the generator dq axis current real-time by the relation of formula (10).Figigure 2 is generator side converter control block diagram.

Figure 2 is generator side converter control block diagram.

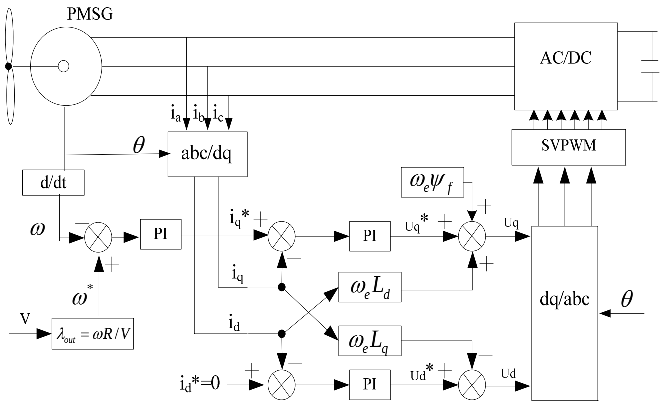


FIG.2 THE CONTROL BLOCK DIAGRAM OF THE GENERATOR-SIDE CONVERTER

In a sampling cycle, suppose the torque change is caused only by the change of current vector. Stator reference voltage u_d^* and u_q^* can be solved by the formula (6), then use SVPWM technology modulate switch signal to realize the control of generator.

Analysis Three-Level Algorithm

According to the reference voltage vector synthesis principle, three level SVPWM algorithm include voltage vector regional judgment, vector action time calculation and time distribution.

1) Judgment of Space Vector Regional

Fig. 3 is three level space vector regional diagram. Through the judgment of reference voltage vector angle, the big triangle area can be determined,then according to the following method to judge the reference voltage vector in which small triangle area[5],[10].

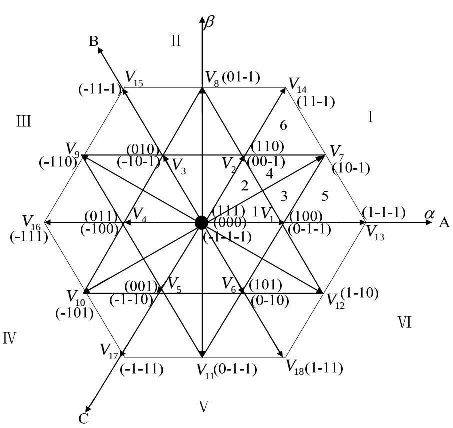


FIG.3 REGIONAL DISTRIBUTION OF THREE-LEVEL SPACE VECTOR

For example sector Ⅰ, six small triangle area distribution shown in figure 4, V_α and V_β is α and β -axis projection of V_{ref}, θ is the angle of amplitude $V_\alpha = V_{ref}\cos\theta$, $V_\beta = V_{ref}\sin\theta$.

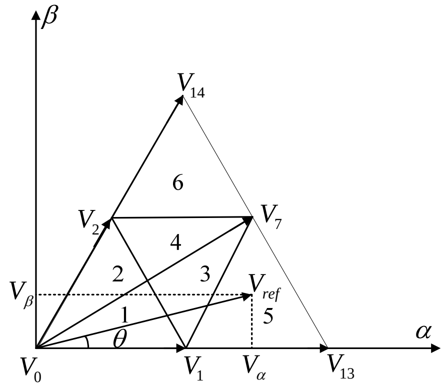


FIG.4 SMALL REGION DIVISION DIAGRAM

When $\theta \le 30^\circ$, α in the sector 1 or 3 or 5,if $V_\beta \le -\sqrt{3}V_a + \frac{\sqrt{3}}{2}V_{dc}$,then α in the sector 1; if $V_\beta \le \sqrt{3}V_a - \frac{\sqrt{3}}{2}V_{dc}$, then α in the sector 5; otherwise in the sector 3.The same as $\theta > 30^\circ$.

2) Calculate The Time of Vector Action

After area judgment , we can get the reference voltage vector area, then the three basic vector V_a, V_b, V_c of synthetic reference voltage vector can be found according to Nearest Triangle Vectors(NTV)[16]. By volt-second balance equations, T_a, T_b, T_c can be solved.

$$\begin{cases} T_aV_a + T_bV_b + T_cV_c = T_sV_{ref} \\ T_a + T_b + T_c = T_s \end{cases} \tag{11}$$

The solutions of T_a, T_b and T_c completed the three-level SVPWM algorithm of basic space vector duration time calculation.

3) Distribution of Time State

The switch state action sequence Need to abide by the following principles:

(a).Each phase bridge arm of inverter can output "1"、"0"、"-1" states. These three transitions between states are not allowed to appear the way of "1" to "-1" directly .That is only allowed from "1" to "0" (or "0" to "1") , and then transit from "0" to "-1" (or "-1" to "0"), as is shown in table 1.

TABLE 1: THE WORKING STATE OF THE THREE-LEVEL INVERTER

S_1	S_2	S_3	S_4	**State**
1	1	0	0	"1"
0	1	1	0	"0"
0	0	1	1	"-1"

(b). Try to reduce the switching frequency. The arrangement of the PWM waveform follow the principles: starting from positive small vector, follow with "0" state transition and change one phase switching action to select the next vector, and to the negative small vector is half of the PWM cycle, and then back to the positive small vector along the original route, thereby a symmetric waveform can be formed in a PWM cycle. Similarly to start from negative small vector.

Control Strategy of Grid-Side Converter

Grid-side converter is controlled by double closed-loop. The purposes are:

(1) The stability of DC voltage;

(2) Inverter's power factor is 1;

(3) The input grid current contain low harmonics[12].

Double closed loop include voltage outer ring and current inner ring. The role of voltage outer ring is to make the active power track the change of the load, because of whether the DC voltage of is constant or not depends on whether active power is balance,therefore the voltage outer ring decide whether the DC bus voltage is stable[11]. Through controlling the current inner ring, the reactive power on the AC side can be regulated. Inverter working in unit power factor can also be realized[13]. We use grid voltage oriented control strategy, make synthesize grid voltage vector oriented in the d axis of synchronization coordinate system. In the $dq0$ axis , the active power and the reactive power of grid-side converter are respectively:

$$\begin{cases} P = 1.5(e_di_d + e_qi_q) = 1.5e_si_d \\ Q = 1.5(e_qi_d - e_di_q) = -1.5e_si_q \end{cases} \tag{12}$$

If $P > 0$, then the grid-side converter works under rectifying state; if $P < 0$, then the grid-side converter works under inverting state; if $Q = 0$, then the grid-

side convertor's power factor is 1.

Figure 5 shows the control block diagram of grid-side.

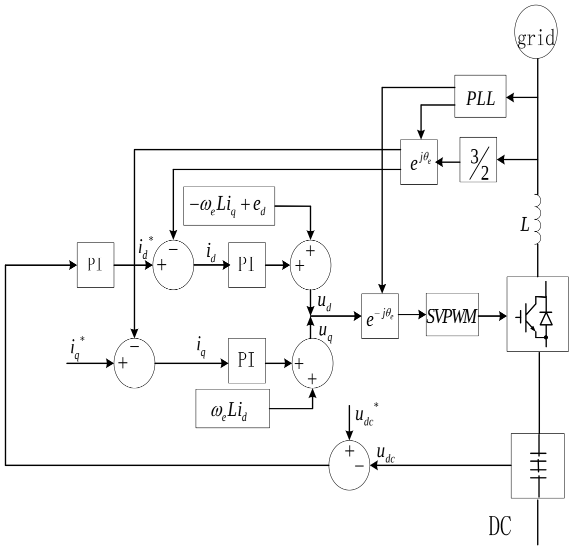


FIG.5 THE SCHEMATIC DIAGRAM OF GRID SIDE CONTROL

Simulating Validate

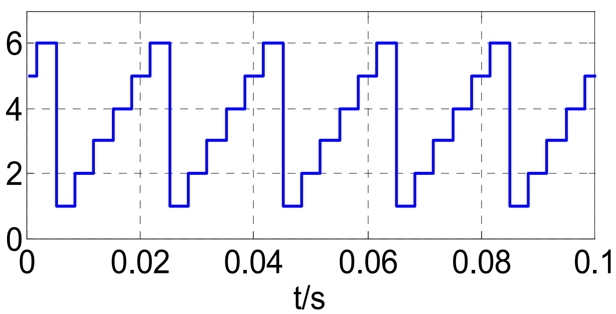
Simulation of Three-level Inverter

In order to proving the correctness of the three level algorithm, we set a three-level inverter in the Matlab, then checking the correctness of the algorithm theory. Chart 2 is the simulation parameter[14,15].

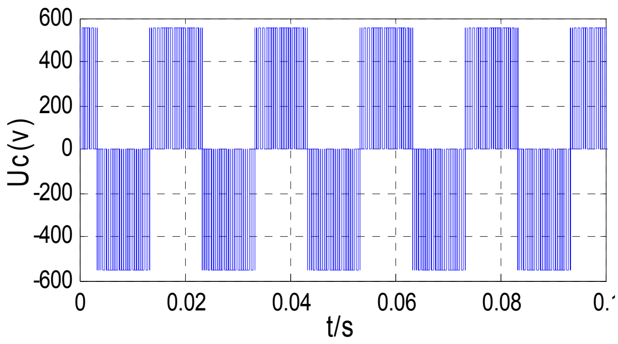
TABLE 2 : THE SIMULATION PARAMETERS OF THE THREE-LEVEL INVERTER

Parameters	Values
DC voltage U_{dc}/V	1100
Filter inductance L/mH	4
Filter capacitor $C/\mu F$	50
Load impedance R/Ω	30
Load inductive reactance X_L/mH	1
Switch frequency f_s/kH_z	10

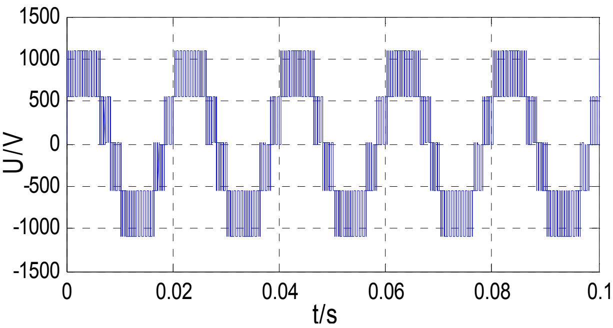
Figure 6 is the simulation results of three-level inverter .



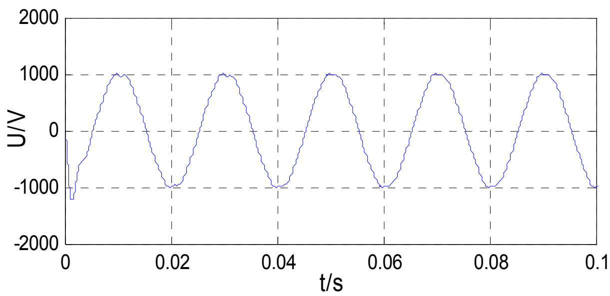
(a) JUDGMENT RESULTS OF BIG SECTOR



(b) C-PHASE VOLTAGE



(c) LINE VOLTAGE BEFORE FILTERING



(d) LINE VOLTAGE AFTER FILTERING

FIG.6 THE SIMULATION RESULTS OF THREE-LEVEL INVERTER

Figure (a) is the real-time simulation result of sector. Through this chart we can see, in a cycle of 0.02s, the reference voltage vector passed 360° area, that means passed every sector. Figure (b) is the step wave of three level , before filtering, the line voltage is five level step wave, after LC smoothing is normal sine wave.

By use of SVPWM modulation mode, The system get five level step voltage waveform. After filtering, voltage waveform close to the sine wave greatly, the harmonic content is very low, at the same time, the adoption of three level greatly reduces the switch frequency and switching loss and improve the efficiency of the system operating. This solved the requirements of low switch frequency of high voltage large capacity inverter due to the problem of switching loss and device performance. It also suitable for requirement for high voltage large capacity inverter of

direct drive wind power system.

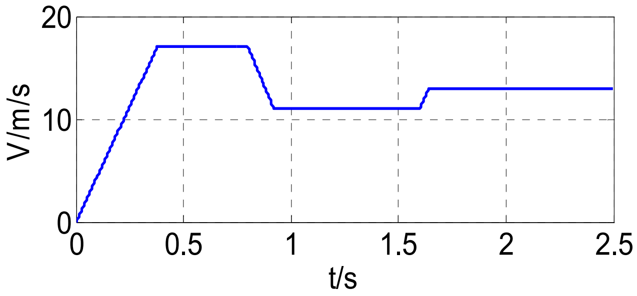
Simulation of PMSG System

Table 3 display the simulation parameters of three-level PMSG system.

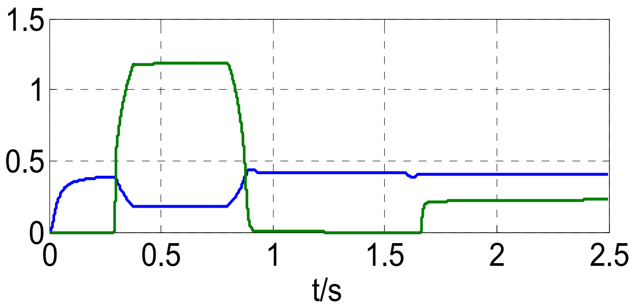
TABLE 3: THE SIMULATION PARAMETERS OF THE SYSTEM

Parameters	Values
Wind turbine radius r/m	34
Rated wind speed $v/(m/s)$	13
Rated speed $\omega/(rad/s)$	2.3
Rated power P/MW	2
Air density $\rho/(kg/m^3)$	1.25
Poles pairs p	30
Stator resistance R_s/Ω	0.006
DC bus voltage U_{dc}/V	1100
DC bus capacitance $C/\mu F$	3000
Rms grid line voltage e_{ABms}/V	690
Grid fundamental frequency $\omega/(rad/s)$	314

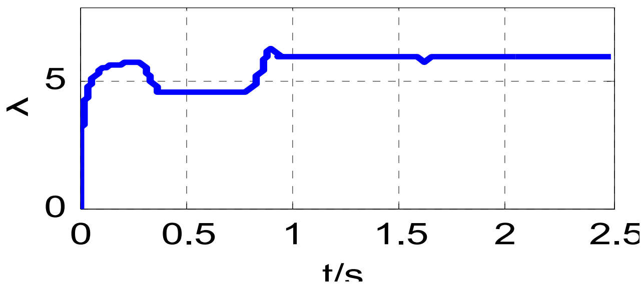
FIGURE 7 SHOWS THE SIMULATION RESULTS OF WHOLE SYSTEM.



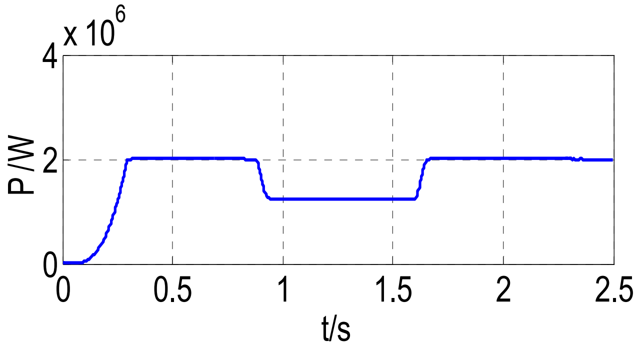
(a) WIND SPEED



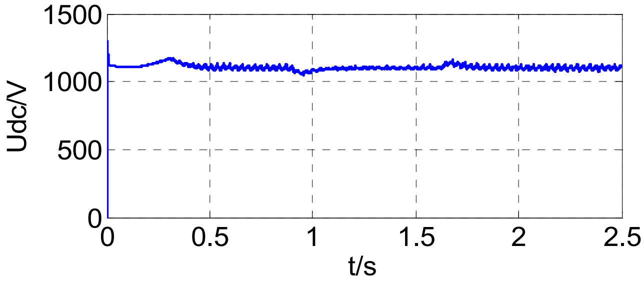
(b) PITCH ANGLE AND WIND POWER UTILIZATION SYSTEM



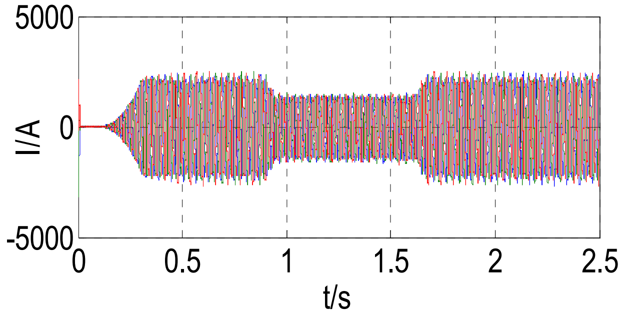
(c) OPTIMAL TIP SPEED RATIO



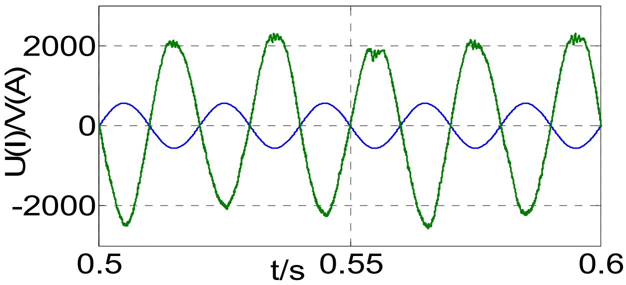
(d) ACTIVE POWER



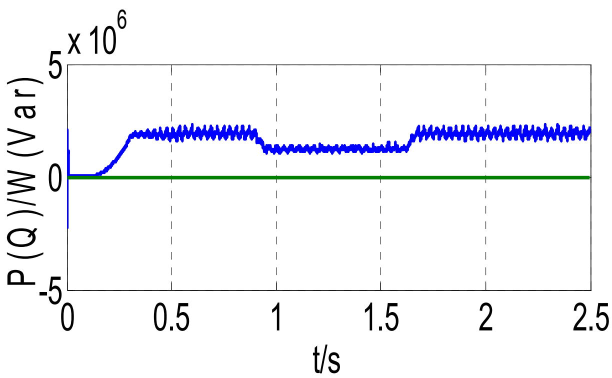
(e) DC-BUS VOLTAGE



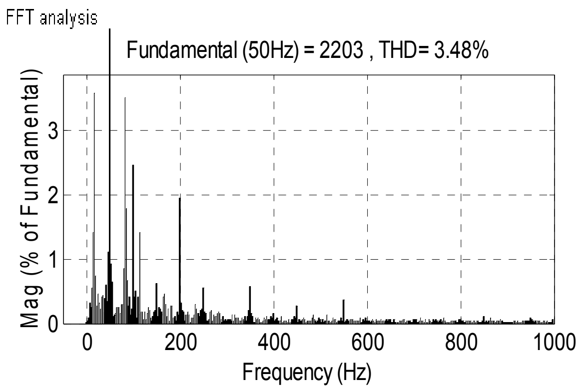
(f) GRID-SIDE THREE PHASE CURRENT



(g) GRID-SIDE A PHASE CURRENT AND VOLTAGE



(h) FEED-IN POWER GRID



(i) FFT ANALYSIS

FIG.7 THE SIMULATION RESULTS OF THE SYSTEM

From (b) to (d) we can know with the change of wind speed , variable plasma distance control all goes well, maximum power tracking effect is obvious. DC-link voltage smooth and steady, grid-side current and voltage phase opposite, this means converter working in contravariant. Fig(h) display feed-in grid reactive is zero, this means inverter's power factor is 1.

Conclusion

Using Three-level NPC Converter, the whole system decreasing output harmonic effectively while improving power capacity of whole equipment, and reducing the voltage stress of switch and the equivalent switching frequency.

Simulations show that generator-side can realize the maximum wind power tracking, and makes the generator operate stably and efficiently by using double closed loop control based on maximum ratio of torque to current. The grid-side converter adopts the vector control of grid voltage orientation, realizing the decoupling control of the active and reactive power. while feed-in grid high quality electrical energy, it also improves the utilization of the whole system.

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